Comparison of SAM and MUSIC performance for unaveraged MEG

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1 Introduction

SAM (synthetic aperture magnetometry) and MUSIC (multiple signal classification) are methods for identifying dipolar sources represented in the covariance of MEG measurements. SAM operates by estimating source and noise power, as a function of position and current vector, from a full-rank covariance matrix [1]. MUSIC finds the locations for which a test dipole is orthogonal to the covariance noise subspace [2]. Thus, MUSIC requires the added nonlinear step of determining where to partition the covariance matrix into signal and noise subspaces. The presence of background brain activity implies that unaveraged MEG measurements have a full rank covariance matrix, with no noise subspace. Despite this, MUSIC has been successfully applied to unaveraged evoked activity, by prewhitening, using the background MEG activity [3]. In many applications, such as clinical MEG recordings of epileptic or focal slow wave activity, it is not always possible to identify MEG segments containing only background brain activity. Consequently, the prewhitening step of Sekihara cannot be easily applied. Nonetheless, it has been suggested that MUSIC can be applied to unaveraged MEG data, after judicious selection of the noise subspace partition. Our study compares the localization accuracy of SAM and MUSIC (for all feasible partitions) for unaveraged MEG. Our test cases include measurement of an electrolyte dipole phantom, for which dipole positions are accurately known, and clinical epilepsy data. The accuracy of both analyses was verified by the dipole phantom over a wide range of conditions. However, using interictal spike data, we were unable to find a rule for selection of the subspace partition rank at which all significant sources could be accurately localized simultaneously by MUSIC. Using the identical MEG data, SAM revealed multiple sources for which the localization uncertainty of each could be predicted from the value of the activation peaks. These uncertainties were small compared with the source localization scatter of MUSIC, corresponding to multiple noise subspace sizes.

2 Methods

2.1 Electrolyte phantom data

A spherical saline-filled electrolyte phantom, with a 13.0 cm inside diameter, was prepared using either of two test current dipoles. Only one dipole was installed for a given measurement. Dipole positions were adjustable, and were set to either (0, 0, 35) mm or (0, 0, 45) mm, relative to the center of the sphere. One test dipole had an electrode separation of 4 mm, while the other had an electrode separation of 9 mm. Dipoles were driven by a 7 Hz sinusoidal adjustable current source, producing dipole moments in the range from approximately 0.5 to 1000 nA-m. A 151-channel whole-cortex MEG system (CTF Systems Inc.) was used for measurements, in the unshielded open environment. This system had a nominal SQUID noise of 5 fT-Hz$^{-1/2}$, above 1 Hz. Each data acquisition consisted of 100 trials of 1.0 second duration. A sample rate of 625 Hz and a bandwidth of DC to 40 Hz were used.

2.2 Epilepsy data

Interictal spike data were recorded using a 151-channel whole-cortex MEG system. Informed consent was obtained from the patient. Two recordings consisting of ten 10.0 second epochs were acquired at a sample rate of 625 Hz (bandwidth DC-150 Hz), with the patient in the reclining position. All measurements were made in an unshielded environment. Each recording contained an average of 55 interictal spikes.

2.3 SAM analysis

SAM analysis of the dipole phantom data was a two-step procedure. First, a covariance matrix was computed for each set of data, for the 5 to 9 Hz frequency band (i.e., centered on the 7.0 Hz signal). Next, the SAM algorithm was used to map pseudo-Z^2 values (the ratio of projected source power to noise power) at 1 mm intervals [1]. A cubic region with 40 mm sides was mapped, centered on the nominal dipole coordinates. Sources were identified by searching for the voxel having the maximum value. The difference between its location and the nominal dipole location was tabulated. The SAM

Table 1: *Experimental localization error (deviation from the nominal dipole coordinate) for electrolyte current dipole phantom is tabulated as a function of dipole moment, dipole length, and dipole depth. The MUSIC noise subspace rank is 50 of 151.*

a) 4 mm Dipole at 0, 0, 35 mm		
Moment Q (nA-m)	**MUSIC dR (mm)**	**SAM dR (mm)**
0.7	11.7	14.1
3.4	6.3	5.7
9.8	4.9	4.1
17.9	1.0	1.7
43.6	2.2	2.2

b) 4 mm Dipole at 0, 0, 45 mm		
Moment Q (nA-m)	**MUSIC dR (mm)**	**SAM dR (mm)**
0.6	14.3	17.2
5.0	3.2	1.7
7.9	3.2	2.8
8.2	3.0	1.4
19.8	2.2	2.2
42.8	2.0	1.0
106.8	2.2	1.8
230.0	2.0	1.0
486.0	2.2	2.4

c) 9 mm Dipole at 0, 0, 45 mm		
Moment Q (nA-m)	**MUSIC dR (mm)**	**SAM dR (mm)**
2.0	9.7	10.8
10.0	1.0	1.4
19.0	2.2	2.0
40.0	2.0	1.4
106.0	2.0	0.8
250.0	2.0	1.0
520.0	1.0	2.8
1125.0	2.0	3.0

analyses employed a forward solution for a current dipole in a homogeneously conducting sphere, with 7^{th}-order integration over the flux transformer coils areas.

SAM analysis of the epilepsy data was accomplished using a similar two-part procedure. The covariance matrices were computed from all 100 seconds of data, in a 25 to 50 Hz bandpass. This frequency range was selected to emphasize the interictal spike activity, providing good separation of spikes from the background brain rhythms. The pseudo-Z^2 values were then mapped by SAM over the entire head at 5 mm intervals. From this, the statistically significant maxima were identified, and new maps computed over a smaller region of interest at 2 mm intervals, centered on each of the maxima. A multiple local sphere model was used, with a unique sphere origin for each primary sensor. This model was based upon the patient's head boundary, as extracted from the MRI. The forward solutions also used 7^{th}-order field integration over the coil area.

Table 2: *Localization difference of MUSIC, as a function of noise subspace rank, relative to SAM localization of the same sources. Failure to find the sources within 50 mm of the SAM coordinates is shown as a dash.*

Epilepsy MEG Data		
MUSIC Noise Rank	**Source 1 dR (mm)**	**Source 2 dR (mm)**
10	3.0	8.6
20	3.5	-
30	3.6	9.9
40	17.3	-
50	3.7	-
60	4.6	-
70	3.7	15.8
75	3.0	-
80	4.7	-
85	4.4	-
90	5.1	12.6
100	4.9	-
110	7.0	12.2
120	8.1	6.4
130	-	-
140	-	-

2.4 MUSIC analysis

All MUSIC analyses utilized the corresponding covariance matrices that had already been generated for the SAM analyses. The eigenvalue spectrum was obtained from the covariance matrices, following eigendecomposition. The eigenvectors for the noise subspace were selected. Lastly, the MUSIC localizer function was evaluated at 1 mm intervals for the dipole phantom and 2 mm for the epilepsy data, within the same regions of interest used for the corresponding SAM volume images. The distance between the nominal coordinates of the dipole and the maximum voxel was tabulated for the dipole phantom data. The distance between the SAM and MUSIC maxima was tabulated as a function of noise subspace rank, for the epilepsy data. An optimal noise subspace rank (n=50) was determined from the eigenvalue spectrum, for the dipole phantom measurements. Forward solution calculations for the SAM and MUSIC cases used identical functions.

3 Results

The electrolyte phantom localization errors, for both SAM and MUSIC, were uniformly less than 5 mm, for all dipoles with moments greater than 5 nA-m. All results are summarized in Table 1. At large SNR, typical of averaged MEG, localization of the dipole phantom by SAM and was quite similar. Both methods accurately identified the source coordinates. With declining SNR, MUSIC became sensitive to the noise subspace rank – possibly due to environmental noise seen in the unshielded environment.

The relative performances of SAM and MUSIC were quite different for the epilepsy data. SAM localized two statistically significant sources of interictal spiking, approximately 22 mm apart, in the right hemisphere. Both sources could be observed in the band-limited time series, and each had a unique field map. Since the SAM localization accuracy could be predicted from the pseudo-Z^2 values of the peak voxels, the MUSIC results, as a function of noise subspace rank (Table 2), could be compared with the SAM sources.

4 Discussion

The experimental accuracy of MUSIC, using real MEG data, is not a smooth function of noise subspace rank. The eigenvalue spectra for the dipole phantom and epilepsy MEG data are shown in Figure 2a. Despite measurement in the unshielded environment, a transition can be found between the signal and noise subspaces for the dipole phantom measurements. The eigenvalue spectrum for spontaneous brain activity decays more slowly. Nonetheless, based on the spectrum, one is tempted to select a partition after the 40 or 50 most significant eigenvalues. Our results show this approach incorrect. When multiple dipoles are active within a small space, MUSIC tended to favour just one source, showing no maxima for the remaining sources. This is illustrated in Figure 1. Adjusting the noise partition affected which source was dominant as well as the magnitude of the displacement from the SAM peaks (Figure 2b and 2c). Two regions of

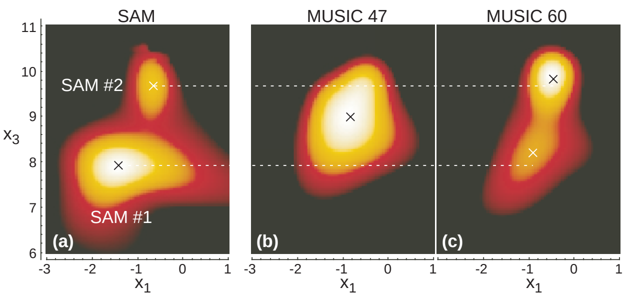

Figure 1: *SAM shows two source peaks in the left hemisphere, separated by about 22 mm (a). MUSIC images at noise subspace ranks 47 (b) and 60 (c) demonstrate the variability of MUSIC localization as a function of rank.*

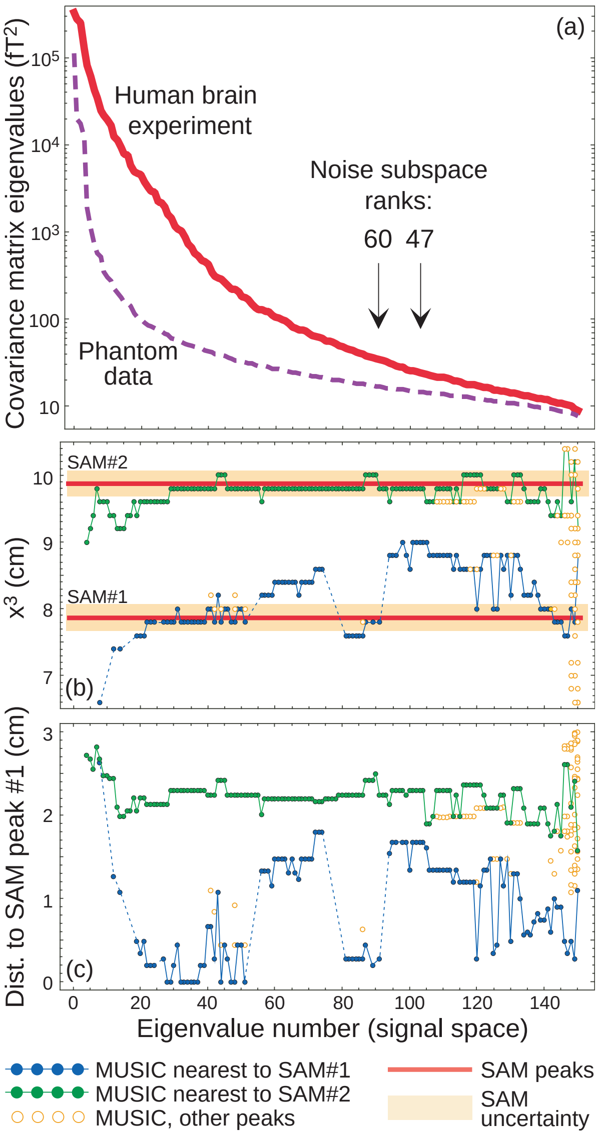

Figure 2. a) *A well defined transition between the signal and noise subspaces is shown for the eigenvalue spectrum of the dipole phantom data. The epilepsy MEG eigenspectrum shows no sharp transition.* b) *The distance (along the z-axis) between sources localized by SAM, and those found by MUSIC, are plotted versus signal subspace rank for MUSIC (noise subspace rank is 151 minus signal subspace rank). The positional uncertainty of the SAM sources is denoted by the coloured band* c) *The displacement of the MUSIC solutions from one of the SAM peaks shows two regions where solutions are in agreement. MUSIC may identify only one source (denoted by dashed lines) or find additional source peaks (open circles).*

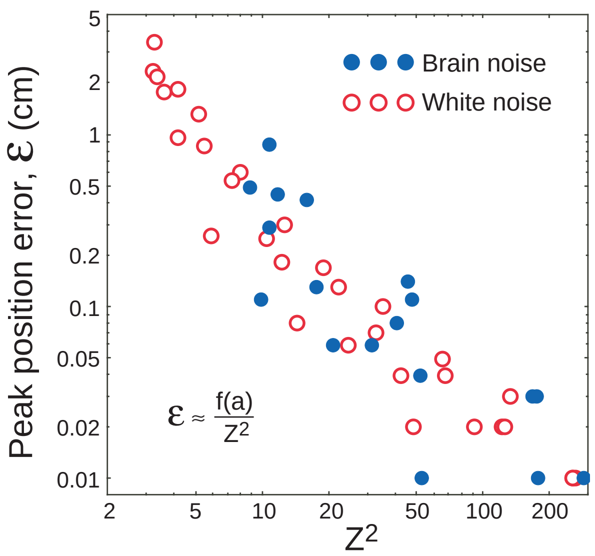

Figure 3: *The position uncertainty of SAM source maxima is presented as a function of* Z^2 *(the ratio of projected source power to projected noise power). Simulated sources of varying depth are superposed on either white noise or measured brain noise. This error is also a function of source depth (a). Hence the scatter in this uncertainty plot.*

noise subspace rank could be found for which the differences between MUSIC and SAM were small, within the uncertainty of the SAM source localizations. However, it does not appear to be feasible to determine the optimal rank blindly, from the eigenvalue spectra, alone. The position of MUSIC peak #1 (Figure 2c) fluctuates by more than 15 mm as a function of the noise subspace rank. Furthermore, within these two zones of agreement, MUSIC occasionally identifies spurious peaks.

In the absence of correlated noise and in the limit of infinite integration time, SAM has no positional error. Although the dipole phantom measurements were made in the presence of environmental (correlated) noise and finite integration time, both SAM and MUSIC localized the phantom dipole better than did a simple dipole fit. Where a good solution could be obtained, dipole fitting tended to show the source deeper than its mechanically determined coordinate. This may have been a consequence of the finite length of the test dipole. That is, the source appears as a line current (of either 4 or 9 mm length) rather than as a point current dipole. This hypothesis was borne out when comparing results for test dipoles of different lengths. When energized with high current (implying high SNR), SAM and MUSIC tended to degrade. Specifically, the pseudo-Z values of SAM and MUSIC localizer decreased as moment increased. This indicates that the signal-space vector of the measurement does not correspond accurately to that of the forward solution. The pseudo-Z and MUSIC localizer values were significantly larger for the 4 mm dipole than for the 9 mm dipole.

The most obvious concern in comparing SAM and MUSIC for the epilepsy example is whether the SAM source peaks correctly represent the true source locations. We have previously shown that, in the presence of correlated noise, the peak position error is predictable from the pseudo-Z^2 value of each SAM peak, and the source distance from the center of the local sphere (shown in Figure 3). Based on this relationship, the SAM source peak Z^2 values in the epilepsy images correspond to a maximum localization error of approximately 3 mm for either source. Thus, the comparison of MUSIC localization errors against the coordinates found by SAM is appropriate. Furthermore, the MUSIC result for source #1 (Figure 2b and c) fluctuates widely, not giving any indication as to the correct position of the peak. Only for peak #2 is the MUSIC result stable over a wide range of eigenvalues. We conclude that SAM is applicable to both averaged and unaveraged MEG data, whereas MUSIC performs best with data for which a distinct transition between signal and noise subspace can be identified.

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